Analysis of Hot-Potato Optical Networks with Wavelength Conversion

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***Abstract*—The performance of wavelength routed optical networks (WRON's) employing packet switching critically depends on packet contentions at the intermediate nodes. This paper shows that, when the active nodes are provided with a number of optical receivers/transmitters equal to the number of wavelengths, routing without buffers, known as *hot-potato* [1], in conjunction with full wavelength conversion becomes an interesting option to solve contentions in packet switching WRON's with regular meshed topologies, such as Manhattan Street (MS) network and ShuffleNet (SN). We analytically compare three implementations of the access function: 1) local arrivals are centrally managed with tunable transmitters, 2) local arrivals are centrally managed with fixed transmitters, and 3) local arrivals are evenly split among fixed, independently managed transmitters. The analysis shows that the simpler access scheme 3), surprisingly, gives better throughput/delay results at high loads than the centrally managed schemes. Results also indicate that, by using more than four wavelengths, a 64-node MS or SN network can work at full load with a delay which is within one hop of its lowest achievable value. The probability of deflection can be made quite low by increasing the number of wavelengths. Another interesting finding is that delay-line optical buffers at the node are a much more effective way of solving contentions than using wavelength conversion: four or more wavelengths are needed in nodes without buffers and with wavelength conversion to match the performance of nodes with one delay-line optical buffer per wavelength and without wavelength conversion. However, optical buffers increase the accumulation of intraband crosstalk and amplified spontaneous emission noise, while wavelength conversion can provide noise suppression and signal reshaping. Hence, in WRON's with a small number of wavelengths, and when the transmission is feasible, it may be preferable to use optical buffers without wavelength conversion. On the other extreme, buffers are not needed with a large number of wavelengths and with full wavelength conversion.**

***Index Terms*—Deflection routing, wavelength conversion, wavelength routing.**

I. Introduction

THE performance of packet switched multihop optical networks critically depends on the temporary blocking of packets at the nodes caused by routing contentions. Such blocking is usually handled by buffering the packets waiting for the correct output fiber to become available. If buffers are insufficient, the packet is either discarded and lost, or misrouted (deflected) [1]. Wavelength conversion is another technique to handle blocking in multiwavelength optical networks: if the correct output on the wavelength the packet is coming from is not available, the packet may be converted to another available wavelength on the desired output fiber.

Wavelength conversion has been shown to reduce the probability of blocking in both circuit-switching [2], [3] and packet switching wavelength routed optical networks (WRON's) [4], [5]. The effectiveness of such reduction critically depends on the topology, and meshed topologies enjoy the largest gain from wavelength conversion [2].

This paper analyzes the performance of packet switching WRON's without buffers and with wavelength conversion. It is shown that, when the active nodes are provided with a number of optical receivers/transmitters equal to the number of wavelengths, routing without buffers, known as *hot-potato* [1], in conjunction with wavelength conversion becomes an interesting option for meshed topologies such as Manhattan Street (MS) network and ShuffleNet (SN).

The multiwavelength multihop network under study can be thought of as a stack of n_w identical parallel networks, one per wavelength. Packets can be routed from one network to the other through wavelength conversion at each node. A simple but rigorous teletraffic analysis based on the structure of the optical node is provided. Each node performs both access and routing functions. Access consists of the regulated transmission of the n_w packet streams of which the node is source, which are handled by n_w optical transmitters. Routing consists of the proper selection of the output wavelength and fiber both for transiting and for locally generated packets. We assume *full* wavelength conversion, i.e., every packet can be converted to any of the n_w available wavelengths.

We analytically compare three schemes for the access function:

1) the locally generated packet streams are jointly handled to maximize the number of injected packets per slot over all wavelengths, and the n_w transmitters are *tunable*;
2) as in point 1), but the n_w transmitters are *fixed*, one per wavelength;
3) each of the n_w locally generated packet streams is associated with a transmitter, and handled independently of the other streams. The transmitters are *fixed*, one per wavelength;

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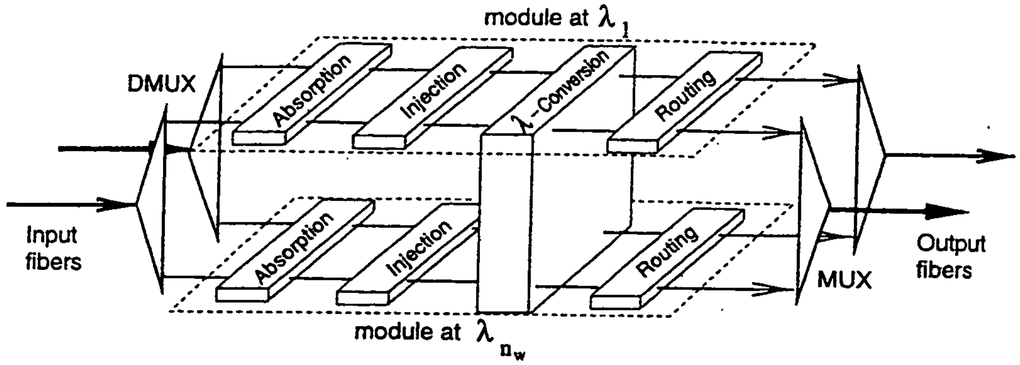

Fig. 1. Logical structure of the node.

The analysis shows that the simpler, less greedy[1] access scheme 3) gives better throughput/delay results at high loads than the more complex schemes 1) and 2). This is due to the fact that access is performed independently of routing, and before it. Hence, maximization of the number of injected packets may reduce the contention resolution capability of the wavelength conversion block.

Results also show that slotted hot-potato meshed networks with 64 nodes with more than four wavelengths and wavelength conversion can work at full load with a delay which is within one hop from its lowest achievable value (no deflections). The probability of deflection can be made quite low by increasing the number of wavelengths.

The paper also shows that delay-line routing buffers at the node are a much more effective way of solving contentions than using wavelength conversion: four or more wavelengths are needed in nodes without buffers and with full wavelength conversion to match the performance of nodes with one delay-line optical buffer per wavelength and without wavelength conversion. However, delay-line optical buffers increase the accumulation of intraband crosstalk and ASE noise, while wavelength conversion can provide noise suppression and signal reshaping [6], [7]. Hence, in WRON's with a small number of wavelengths it may be preferable use optical buffers without wavelength conversion, when the transmission is feasible. On the other extreme, buffers are not needed with a large number of wavelengths and with full wavelength conversion. Hybrid solutions using both buffers and wavelength conversion [4] may be the best solution in intermediate cases, but further work is required to quantify the tradeoff.

The remainder of the paper is organized as follows. Section II presents the structure of the node. Section III details the three access blocks. Section IV gives the wavelength conversion algorithm used at each node. Section V presents the detailed analysis for access scheme 1). Section VI extends the analysis to the other two access schemes. Results for the regular meshed topologies MS and SN are presented in Section VII, and Section VIII contains the conclusions.

II. Node Structure

The performance analysis will refer to the logical structure of the node shown in Fig. 1. The node has two input and output fibers. The incoming n_w wavelengths from each input fiber are spatially demultiplexed and sent to a stack of n_w modules. Within each module, the functions of packet drop (absorption), add (injection), wavelength switching (λ-conversion), and space switching (routing) are sequentially and *independently* performed. Packets are finally remultiplexed onto the output fibers. The node operations are time slotted, and packets (called *cells*) have a fixed size and are aligned at the node inputs.

Shortest-path routing is adopted. For each cell, one or both output fibers may lead to its destination in a minimum number of hops. A cell that can take either output is a *don't care cell.* A cell that has only one preferred output is a *care cell.* Slots on each wavelength at the input of the node can be empty (E), can carry a cell for the node (FN), or a cell that cares to exit on output 1 (C1) or output 2 (C2), or a don't care (DC) cell.

The absorption block removes the FN cells. It is assumed that there is one receiver per input wavelength, so that all cells destined to the node can be removed.

The injection block transmits the locally generated cells according to its specific access scheme. Injections can take place only on E slots.

The wavelength conversion block interconnects all modules, and has the task of rearranging the cells on the various wavelengths so as to eliminate as many output fiber contentions as possible within the modules. A contention occurs in a module when there are two care cells with the same output preference, either (C1, C1) or (C2, C2).

Finally, the routing block in each module is a simple unbuffered 2×2 switch. In case of output contention, one of the cells is selected at random and deflected to the undesired port [1].

A. Implementation with an Optical Packet Switch

One possible physical implementation of the above logical node structure is shown in Fig. 2. Some power from the optically demultiplexed inputs is tapped off for electronic header processing and control. Suitable electrical signals are generated in this block to control the optical switches. In each module (delimited by a dashed box in the figure), cells without contention and not destined to the node flow to the 2×2 routing switch. Cells destined to the node are received (ORX), and cells selected for wavelength switching are routed to a rearrangeably nonblocking (RNB) optical

[1] A *greedy* access scheme is one that tries to maximize the number of injected packets at each slot.

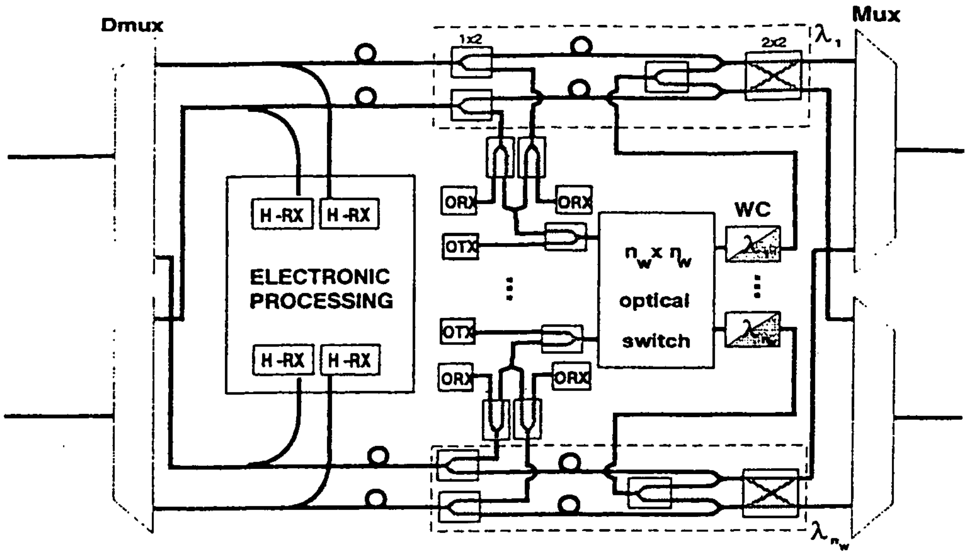

Fig. 2. Physical implementation of the node, utilizing an optical $n_w \times n_w$ switch. Symbols used: H-RX—header receiver; 1×2 and 2×2—optical switches; OTX—optical transmitter; ORX—optical receiver; WC—optical wavelength conversion; Mux/Dmux—optical multiplexer/demultiplexer.

$n_w \times n_w$ switch,[2] whose outputs are connected to fixed optical wavelength converters (WC). The switch acts as a selector for the appropriate WC for the cell.

A fixed optical delay must be present on the optical paths inside each module, in order to keep synchronization with cells that get wavelength converted.

Although we placed the optical transmitters (OTX) before the optical $n_w \times n_w$ switch for consistency with the logical node scheme, for a better quality of the injected optical cells it is advisable to place the OTX's after the switch. In this case, the wavelength conversion algorithm controlling the $n_w \times n_w$ switch (which knows ahead of time which cells are ready at the OTX's) acts *as if* the local cells were placed *before* the switch, although they are physically placed only *after* it.

Note that this scheme uses n_w OTX's, n_w ORX's, and n_w WC's. The wavelength converters can be omitted (with potential cost savings) if the switching is performed in the electronic domain, as shown next.

B. Implementation with an Electronic Packet Switch

An alternative physical implementation of the logical node structure is shown in Fig. 3, where the header recognition and processing block has been omitted for simplicity. Thick lines indicate optical paths, thin lines electronic paths. The main difference from Fig. 2 is the presence of an RNB *analog* $n_w \times n_w$ *electronic* switch. In this semitransparent node, cells without contention and not destined to the node remain in the optical domain while cells both destined to the node and selected for wavelength switching are converted to the electronic domain by the same receiving interfaces (PD), and routed either to the receiving blocks (RX) for detection, or to the electronic switch. Either the signals out of the electronic transmitters (TX) or those from the PD's drive the modulators of the stack of n_w fixed optical transmitters (OTX), which thus

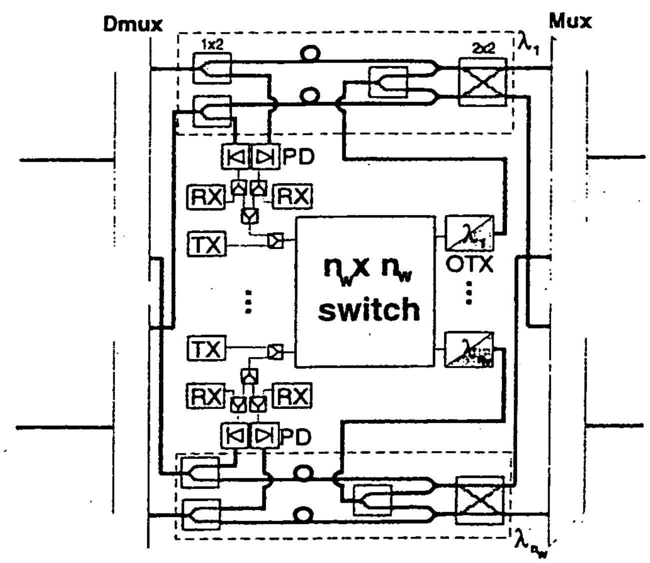

Fig. 3. Physical implementation of the node, utilizing an electronic $n_w \times n_w$ switch. Optical paths in thick lines, electrical paths in thin lines. Notation as in Fig. 2. Other symbols used: PD—photodetector; TX/RX—electronic transmitter/receiver; header recognition block omitted for simplicity.

serve also as wavelength converters. A fixed optical delay must be present on the completely optical paths, in order to keep synchronization with cells that get electronically converted and wavelength switched. Such analog passage to the electronic domain can be fast, since the cell header has already been read, and can provide noise suppression and reshaping [7]. The issue as to whether the cost of the analog unbuffered electronic switch capable of carrying, say, 10 Gb/s signals per input port can be lower than that of its optical counterpart plus that of the stack of optical wavelength converters is open, and the answer depends on technology [8].

III. Access Schemes

Consider the logical node structure in Fig. 1. The node is source of n_w local cell streams.

[2]Since the system is slotted, and slots are aligned at the input, the switch settings must be changed at each slot. Thus, a strictly nonblocking switch is not needed, and a RNB switch serves the purpose.

First we will assume the node has n_w *tunable* optical transmitters and consider a pooled management of the injection of local cells (PI) in order to maximize the number of injected cells per slot over all wavelengths. Let $0 \leq G \leq n_w$ be the number of local cell arrivals per clock. Let $0 \leq V \leq 2n_w$ be the number of empty input slots after the absorption block. Then a number $I = \min(G, V)$ of new cells are injected at the node, placed at random among the available V empty slots. We assume cells in excess of the available injection slots are discarded. In the PI scheme it may happen that two new cells are injected on the same wavelength.

Next, we will still consider a pooled management of injections, but the node has n_w fixed transmitters, one per wavelength. We label this case as pooled per-wavelength injections (PPWI). A transmitter can inject a new cell only if there is at least one empty slot at that wavelength after the absorption block. Let $0 \leq W \leq n_w$ be the number of transmitters that can inject a new cell. Then a number $I = \min(G, W)$ of new cells are injected at the node, placed at random among the W available wavelengths. Cells in excess of the available wavelengths are discarded.

Finally we will consider the simplest case of independent per-wavelength injections (IPWI): we assume the node has n_w *fixed* transmitters, and each transmitter handles a single local cell stream, independently of the other transmitters at the node. If local blocking at that wavelength occurs, the cell is discarded. Such a scheme is the simplest, and does not maximize the overall number of injections.

Note that the physical node implementation in Figs. 2 and 3 refers to schemes PPWI and IPWI, while scheme PI would require extra hardware, although it will be shown to perform worse than the other schemes.

IV. Wavelength Conversion Algorithm

To solve contentions and avoid deflections at the routing block, the node controller after header detection uses the following algorithm to determine the appropriate wavelength conversion of cells.

/* BEGIN */

Step 1)

Group modules with contending input cells according to the cells' preference in two sets: the set $\mathcal{A}$ of those whose input cells are (C1, C1); and the set $\mathcal{B}$ with input cells (C2, C2). Let a be the number of elements in $\mathcal{A}$, and b that in $\mathcal{B}$. Assume that $a \geq b$ (reverse the reasoning otherwise).

Group modules without input contention in two sets: the set $\mathcal{C}$ of those that do not contain a single C1 input cell, and the set $\mathcal{D}$ of those that do. Let c be the number of elements in $\mathcal{C}$.

Step 2)

Select at random b modules in $\mathcal{A}$. For each of them, swap one of its input C1 cells with one of the input C2 cells of a corresponding module in $\mathcal{B}$, thus removing contentions in both modules. Swapping is achieved by interchanging the wavelengths of the two cells. After b swappings, all contentions in $\mathcal{B}$ are removed. If $a = b$ terminate the procedure, else $a - b$ modules with contention are left in $\mathcal{A}$. To further reduce contentions, repeat the swapping between those $a - b$ modules and the modules in $\mathcal{C}$. If $c > a - b$ all contentions get removed. Else $a - b - c$ contentions are left in $\mathcal{A}$, which will cause $a - b - c$ deflections at the routing block.

/* END */

Note that contentions are never created by swapping. The procedure ends with at most $a \leq n_w$ swappings, that is $2a$ wavelength conversions, and has computational complexity $\mathcal{O}(n_w)$.

V. Analysis

We assume the number G of local cell arrivals per node at each clock is a binomial random variable (RV) with trial number n_w and success probability g, which we indicate with $\text{Bin}(n_w, g)$. This corresponds to having n_w independent Bernoulli fluxes of intensity g. We assume the destinations of new cells are independent and uniformly distributed over all network nodes excluding the source. Let P_{dc0} be the fraction of DC destinations, i.e., those that can be reached from the source from either output link in the same minimal number of hops. We assume the topology of the network is regular, which ensures that half of the remaining care destinations will be for output 1 and half for output 2.

Define u as the input slot utilization, i.e., the probability that a slot from an input fiber carries a cell. Let P_{dc} be the probability that such input cell is DC, and r the probability that such input cell is FN. At every clock, label the slots from the two input fibers (after the absorption block) as I_j, $j = 1, 2, \cdots, 2n_w$. We make here the usual key assumption that the I_j's are independent random variables with identical probability distribution $\text{f}_\text{i} = \{P\{I_j = s\}, s \in \{\text{E, DC, C2, C1}\}\}$ [9]. This assumption leads to accurate results only when the topology is regular and the input traffic is uniform, as in our case. More realistic nonuniform traffic patterns are much more complex to model. The uniform traffic assumption, however, allows simple comparisons of node structure and control algorithms, and the conclusions usually hold true in most nonpathological nonuniform traffic scenarios [10].

From the above definitions, one gets $\text{f}_\text{i} = \{f_i(\text{E}), f_i(\text{DC}), f_i(\text{C})\} = \{1 - u(1 - r), uP_{\text{dc}}, u(1 - P_{\text{dc}} - r)\}$, and it is assumed that, among care cells, outputs 1 and 2 are equally likely.

In the following, we carry on the complete analysis for the case of pooled injections (PI), and in Section VI we consider the simpler PPWI and IPWI options.

A. Slot Utilization

At steady state and with uniform traffic, at each node and clock time, the average number of absorbed cells per wavelength S_{abs} must equal the average number of injected cells S_{inj}, their common value being the throughput per node per wavelength S. Since on average ru cells destined to the node reach each wavelength from each input and are all absorbed, we have $S_{\text{abs}} = 2ru$. By Little's law, the throughput per wavelength in two-connected networks is easily shown to be $S = 2u/H$ [9], where H is the average number of hops, so that one immediately gets: $r = 1/H$.

Recalling from Section III that $I = \min(G, V)$ is the number of injected cells in the PI case, the average number of injections per clock at the node can be expressed as:

$$n_w S_{\text{inj}} = E[\min(G, V)] \quad (1)$$

where by the independence assumption the RV V is $\text{Bin}(2n_w, f_i(E))$. The expectation in (1) is evaluated by conditioning on G as follows:

$$E[\min(G, V)] = \sum_{i=1}^{n_w} P\{G = i\} \times \left(\sum_{j=0}^{i-1} jP\{V = j\} + i\left(1 - \sum_{j=0}^{i-1} P\{V = j\}\right)\right). \quad (2)$$

Solving the equation $S_{abs} = S_{inj}$ gives an implicit expression for u

$$u = \frac{HE[\min(G, V)]}{2n_w}. \quad (3)$$

B. Deflection Probability

Because of the regularity of the considered topologies and the uniform traffic assumption, the global network traffic is a merger of independent, statistically identical traffic streams directed to each destination. Any cell will be a *typical* cell, whose trajectory toward destination can be modeled as a random walk in a homogeneous "gas" of interfering cells [9], [11], [12]. We now evaluate the deflection probability d of a flow-through test cell (TC) entering an intermediate node at which it is care, and the deflection probability d_0 of a care TC at its injection node.

Refer to Fig. 1. The flow-through care TC is at one of the $2n_w$ inputs and crosses the absorption and injection blocks, reaching the conversion block.

Since the TC is flowing through, injections can occur only on $2n_w - 1$ slots. Let us fix our attention on an empty slot present at the input of the injection block. We want the probability of the event $\mathcal{U} = \{$the slot at the output of the injection block is filled with a new cell/it was empty at the input$\}$.

Let $\tilde{V}$ be the number of empty slots besides the one we are considering. Then $\tilde{V}$ has a binomial distribution $\text{Bin}(2n_w - 2, f_i(\text{E}))$. Since, given $\tilde{V} = j$ and $G = i$, the probability that our empty slot is filled out of $j+1$ empties is $\min[i/(j+1), 1]$, we have

$$P\{\mathcal{U}\} = E\left[\min\left(\frac{G}{\tilde{V}+1}, 1\right)\right] = \sum_{i=1}^{n_w} P\{G = i\} \times \left(1 - \sum_{j=i}^{2n_w-2} P\{\tilde{V} = j\} + i \sum_{j=i}^{2n_w-2} \frac{P\{\tilde{V} = j\}}{j+1}\right). \quad (4)$$

Therefore, the probability that a slot at the input of the conversion block carries another care cell is

$$f_i'(\text{C}) = f_i(\text{C}) + f_i(\text{E})P\{\mathcal{U}\}(1 - P_{\text{dc0}}) \quad (5)$$

since the slot either already carries a flow-through care, or it is empty and is filled with a new care cell.

Let us now evaluate the deflection probability d. A deflection occurs if the TC enters the conversion block in a module with another competing cell, and the contention is not resolved by the conversion block. Referring to the set labeling in Section IV, the module hosting the TC belongs to set $\mathcal{A}$, where contentions may remain after the block.

Let us consider the configuration of slots at the input of the wavelength conversion block. One module in $\mathcal{A}$ has a contention that involves the TC. Also, there are $a - 1$ more modules in $\mathcal{A}$, b modules in $\mathcal{B}$, and c modules in $\mathcal{C}$. The conversion algorithm has thus $b + c$ modules to swap with modules in $\mathcal{A}$, and if $a > b + c$, then $a - b - c$ contentions in $\mathcal{A}$ cannot be solved. Since modules with a contention are selected at random for swapping, then the probability that the TC belongs to a module in which a contention is not solved is $(a - b - c)/a$.

Hence, the probability P_C that a contention remains in the TC module after the conversion block is

$$P_C = \sum_{\mathcal{S}} \frac{a - b - c}{a} P(a, b, c) \quad (6)$$

where $\mathcal{S} = \{(a, b, c): 1 \le a + b + c \le n_w;\ a > b + c\}$ is the set of feasible triples where contentions remain for the TC,[3] and where $P(a, b, c)$ is the probability of the triple (a, b, c). This can be evaluated as follows. Let $\mathcal{E}_0 = \{$TC has an input contention$\}$. Let $\mathcal{E}_1 = \{$a module is in $\mathcal{A}\}$. Let $\mathcal{E}_2 = \{$a module is in $\mathcal{B}\}$. Let $\mathcal{E}_3 = \{$a module is in $\mathcal{C}\}$. Let $\mathcal{E}_4 = \{$a module is in $\mathcal{D}\}$.

Since injections are operated at random on the available empty slots, the slots at the input of the conversion block remain independent random variables, as they were before injection. Hence, we have (7) shown at the bottom of the next page, where the term in square brackets is a multinomial probability. It is easily seen that

$$\begin{cases} P\{\mathcal{E}_0\} = f_i'(\text{C})/2 \\ P\{\mathcal{E}_1\} = P\{\mathcal{E}_2\} = (f_i'(\text{C})/2)^2 \\ P\{\mathcal{E}_3\} = (1 - f_i'(\text{C})/2)^2 - (f_i'(\text{C})/2)^2 = (1 - f_i'(\text{C})) \\ P\{\mathcal{E}_4\} = 2(f_i'(\text{C})/2)(1 - f_i'(\text{C})/2) \\ \qquad\quad = 1 - P\{\mathcal{E}_1\} - P\{\mathcal{E}_2\} - P\{\mathcal{E}_3\}. \end{cases} \quad (8)$$

[3] For programming purposes $\mathcal{S}$ can be found as follows. Fix $1 \le a \le n_w$ (it must be larger than 0 since the TC is in $\mathcal{A}$). Then select the number of modules in $\mathcal{B}$: $0 \le b \le a - 1$. However it must also be $a + b \le n_w$. Hence, we take $0 \le b \le \min(a - 1, n_w - a)$. Finally we select the number of modules in $\mathcal{C}$: $0 \le c \le (a - b) - 1$. If c is larger than this, all contentions can be eliminated. Also we must have $a + b + c \le n_w$. Hence, the set $\mathcal{S}$ can be expressed as $\mathcal{S} = \{(a, b, c): 1 \le a \le n_w;\ 0 \le b \le \min(a - 1, n_w - a);\ 0 \le c \le \min(a - b - 1, n_w - a - b)\}$.

The TC is then deflected if it loses the coin toss at the routing block, i.e., with probability $d = P_C/2$.

As for the initial deflection probability of a care TC at its injection step, d_0, this is obtained as in (5)–(8), the only difference being in (4), where now G, the number of local cell arrivals per clock excluding the TC, cannot be more than $n_w - 1$, i.e., is distributed as $\mathrm{Bin}(n_w - 1, g)$.

C. Throughput and Delay Evaluation

The previous results can be put together to get the desired expressions of the throughput $T(g)$ and the hop delay $D(g)$ as functions of the parameter g, the generation probability. The procedure involves the solution of a 2×2 system of nonlinear equations. We start with an initial guess of the quantities $[d, d_0]$. Then, given the regular topology, solving an absorbing Markov chain whose states coincide with the network nodes, as detailed in [9], the average number of hops H and the probability of don't care P_{dc} can be easily obtained as functions of $[d, d_0]$ only [9]. Then $r = 1/H$ is obtained. Next $u = u(g, r)$ is evaluated as outlined in Section V-A. Finally, new values for $[d, d_0]$ are obtained as in Section V-B. The process is repeated up to convergence of $[d, d_0]$.

VI. Simpler Access Schemes

The next two subsections extend the analysis to the simpler access schemes PPWI and IPWI described in Section III.

A. Pooled Per-Wavelength Injections

Let us consider the case of pooled per-wavelength injections (PPWI). The number W of wavelengths at which at least one empty slot is at the input of the injection block has a binomial distribution $\mathrm{Bin}(n_w, 1 - (1 - f_i(\mathrm{E}))^2)$. The average number of cells injected per node is, as in (1)

$$n_w S_{inj} = E[\min(G, W)]. \tag{9}$$

Now let us consider the deflection probability of a flow-through care TC. Equations (6) and (7) still hold in this case, but the probabilities of events $\mathcal{E}_0$ through $\mathcal{E}_4$ are different.

Consider event $\mathcal{E}_0$ first. As in (8), we have

$$P\{\mathcal{E}_0\} = (f_i(\mathrm{C}) + f_i(\mathrm{E}) P\{\mathcal{U}\}(1 - P_{dc0}))/2. \tag{10}$$

The probability $P\{\mathcal{U}\}$ that a slot after the injection block is filled with a cell is found as in (4), where $\tilde{V}$ is now replaced by the number $\tilde{W}$ of wavelengths, excluding the TC wavelength, on which an injection is possible. This RV has a binomial distribution $\mathrm{Bin}(n_w - 1, 1 - (1 - f_i(\mathrm{E}))^2)$.

Now consider event $\mathcal{E}_1$. A (C1, C1) after the injection block is possible only if it was already present at the input, or if there was an (E, C1) or (C1, E), and the E was filled with a C1

$$P\{\mathcal{E}_1\} = \left(\frac{f_i(\mathrm{C})}{2}\right)^2 + 2\frac{f_i(\mathrm{C})}{2} f_i(\mathrm{E}) \frac{P\{\mathcal{U}\}(1 - P_{dc0})}{2}. \tag{11}$$

By symmetry, $P\{\mathcal{E}_2\} = P\{\mathcal{E}_1\}$. Now, the probability that the E is filled, $P\{\mathcal{U}\}$, is slightly different from case $\mathcal{E}_0$, since now the number $\tilde{W}$ of available wavelengths for injection (excluding the one under consideration for event $\mathcal{E}_1$) is $\tilde{W} = X + Y$, where RV X is distributed as $\mathrm{Bin}(n_w - 2, 1 - (1 - f_i(\mathrm{E}))^2)$ and accounts for the available wavelengths except the TC wavelength; and where the RV Y is $\mathrm{Bin}(1, f_i(\mathrm{E}))$ and accounts for the TC wavelength.

We use (4) again where $\tilde{V}$ is replaced by $\tilde{W}$

$$\begin{aligned} P\{\mathcal{U}\} &= E\left[\min\left(\frac{G}{\tilde{W}+1}, 1\right)\right] \\ &= P\{Y = 0\} \times E\left[\min\left(\frac{G}{X+1}, 1\right)\right] \\ &\quad + P\{Y = 1\} E\left[\min\left(\frac{G}{X+2}, 1\right)\right]. \end{aligned} \tag{12}$$

Now consider event $\mathcal{E}_3$. We have

$$\begin{aligned} P\{\mathcal{E}_3\} = &\left[\left(1 - f_i(\mathrm{E}) - \frac{f_i(\mathrm{C})}{2}\right)^2 - \left(\frac{f_i(\mathrm{C})}{2}\right)^2\right] \\ &+ \left\{2\left(1 - \frac{f_i(\mathrm{C})}{2}\right) f_i(\mathrm{E}) - f_i(\mathrm{E})^2\right\} \\ &\times \left(1 - \frac{P\{\mathcal{U}\}(1 - P_{dc0})}{2}\right) \end{aligned} \tag{13}$$

because a wavelength after the injection block has no contentions nor C1's if this is true when injections cannot take place [expression in square brackets, similar to that in (8)], or when they can (expression in curly brackets) and a C1 cell is not injected (last expression in brackets). $P\{\mathcal{U}\}$ is as in case $\mathcal{E}_1$.

Finally, to evaluate the initial deflection probability d_0, we use again (6) and (8), where the probabilities of events $\mathcal{E}_0$ through $\mathcal{E}_4$ must be recomputed as follows. Since the TC is generated and injected, then on its wavelength no other injection is possible and thus $P\{\mathcal{E}_0\} = f_i(\mathrm{C})/2$.

In the evaluation of $P\{\mathcal{E}_1\}$ and $P\{\mathcal{E}_3\}$, we note that G in (4) is now distributed as $\mathrm{Bin}(n_w - 1, g)$, and $\tilde{W}$ is distributed as $\mathrm{Bin}(n_w - 2, 1 - (1 - f_i(E))^2)$.

B. Independent Per-Wavelength Injections

Let us consider the cheapest option of noncoordinated per-wavelength injections (IPWI).

$$P(a, b, c) = P\{\mathcal{E}_0\}\left[\frac{(n_w - 1)! P\{\mathcal{E}_1\}^{a-1} P\{\mathcal{E}_2\}^b P\{\mathcal{E}_3\}^c P\{\mathcal{E}_4\}^{(n_w - a - b - c)}}{(m - 1)! l! k! (n_w - a - b - c)!}\right] \tag{7}$$

Here the average number of cells injected per wavelength simply is

$$S_{inj} = g(1 - (1 - f_i(\mathrm{E}))^2) \tag{14}$$

which is the equivalent of (1). For this case there is a closed-form expression for u [9]

$$u = \frac{\sqrt{r^2 + g^2(1-r)^2} - r}{g(1-r)^2}. \tag{15}$$

In the evaluation of the deflection probability d of a flow-through care test cell, (6) and (7) still hold, and the probabilities of events $\mathcal{E}_0$ through $\mathcal{E}_4$ are the same as in the PPWI case, (10), (11), (13), by simply changing $P\{\mathcal{U}\}$ in g. The evaluation of the initial deflection probability d_0 is identical to that of d, the only difference being in the expression $P\{\mathcal{E}_0\} = f_i(\mathrm{C})/2$ as in the PPWI case.

VII. Results and Discussion

In this section we will give teletraffic performance curves for a 64-node ShuffleNet (SN64) and a 64-node Manhattan Street network (MS64), which are known to have very similar topological properties, and hence similar performance [10].

Monte Carlo simulations were performed [5] to validate the accuracy of the analytical models, according to the method in [11]. Simulation statistics were collected for 30 000 clock cycles, after discarding 3000 initial cycles to allow for transients to die out.

Fig. 4 shows propagation delay H in number of hops against throughput per wavelength S for increasing number of wavelengths with the IPWI access scheme.

The discrepancies in results between theory and simulation are in the range from 0 to 0.3 hops at maximum throughput. The discrepancies are mostly due to traffic inhomogeneities: although the networks are regular, even in uniform traffic there is a slight imbalance in the number of C1 and C2 cells received from the two input links of a module, so that the assumption of identical input distributions is violated [13]. Similar results have been obtained for the other two access schemes.

Fig. 5 compares all three access schemes in terms of the analytical curves for H versus S. The costly pooled injection (PI) scheme (solid lines) performs worse than the simpler PPWI and IPWI schemes (circles and dashed lines, respectively). Since IPWI and PPWI perform very similarly, to avoid confusion PPWI is shown only for $n_w = 1, 2, 3$.

Note that the average hop-delay H with wavelength conversion improves with the number of wavelengths n_w. The reason is that cells in contention have the possibility of being converted to available slots on other wavelengths without contention. The probability of deflection then decreases and so does the propagation delay, causing an increase in throughput.

The first substantial improvement occurs when increasing from one to two wavelengths, and then gradually, the improvement becomes more and more marginal for larger values of n_w. This is similar to the improvement obtained in single-wavelength deflection routing networks when adding routing buffers at the node [10], since wavelength conversion solves contentions and thus avoids deflections, as buffers do.

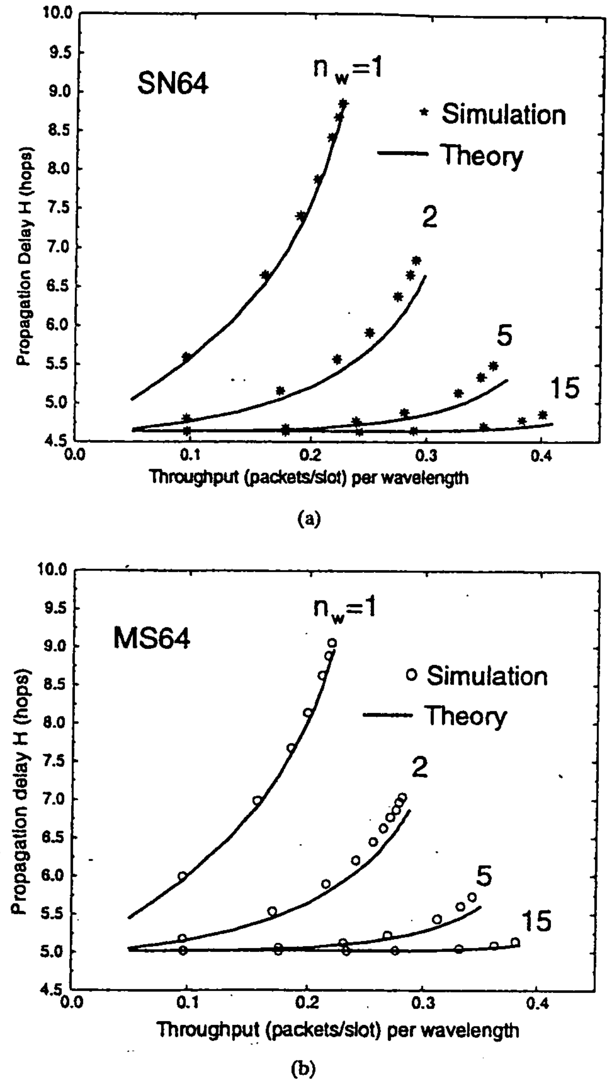

Fig. 4. Simulated and theoretical average hop-delay H versus throughput with the IPWI access scheme for (a) SN and (b) MS.

Note that using more than four wavelengths brings the hop count H of within one hop of its lowest (zero deflection) value.

Fig. 6 shows deflection probability against link load u. We note that at light loads the PI scheme gives lower deflection probability, but as the load increases the less greedy schemes PPWI and IPWI give lower deflection probability, although the difference is small. This is because less injections allow the conversion block to solve contentions more efficiently, thus reducing deflections. This means that a less greedy access strategy does improve the throughput/delay performance at high load, a result similar to that obtained in [9] when comparing a hold-up access scheme to the traditional greedy access in single-wavelength hot-potato networks. In any case, PPWI and IPWI behave almost identically. Thus, the simpler IPWI scheme should be preferred.

As in Fig. 5, we note that the effect of increasing the wavelengths is similar to that of increasing buffers in single-wavelength networks. We note for example that we can

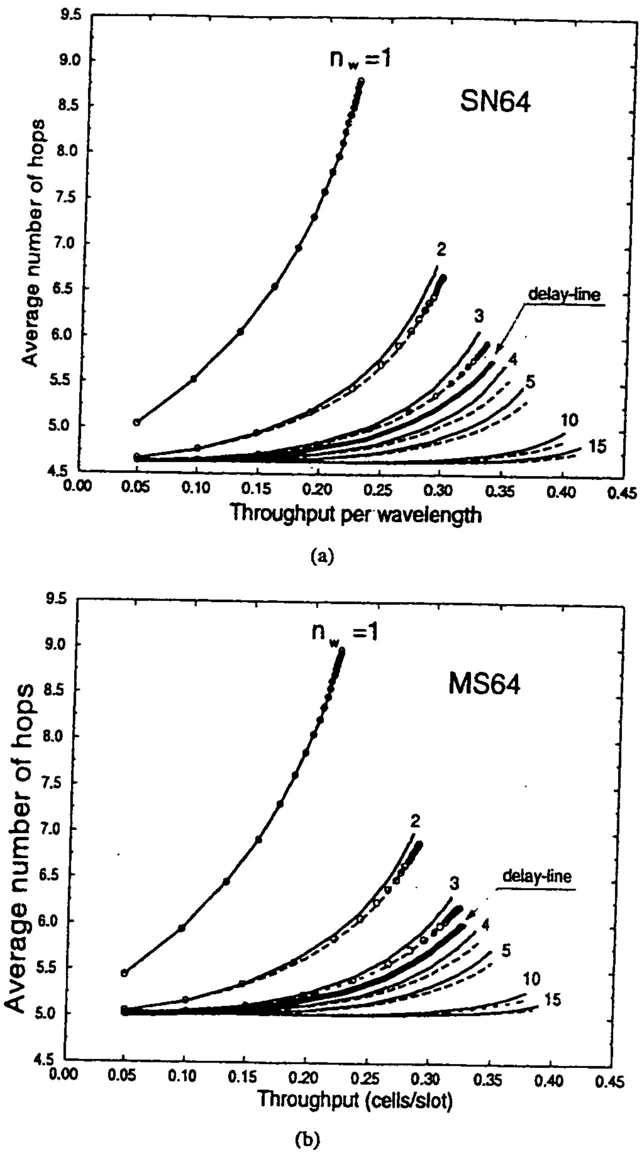

Fig. 5. Average number of hops H versus throughput per wavelength S [cells/slot] in (a) a 64-node ShuffleNet and (b) a Manhattan Street. Number of wavelengths as a parameter: $n_w = 1, 2, \cdots, 15$. Solid lines—pooled injections (PI); circles ($n_w = 1, 2, 3$)—pooled per wavelength injections (PPWI); dashed lines—independent per-wavelength injections (IPWI); delay-line—indicates a single wavelength network with one optical buffer per node [11].

keep the deflection probability below 10^{-9} with $n_w = 15$ wavelengths only at loads below $u = 0.2$ in SN and 0.22 in MS. As the load increases, deflections set in, even with a large number of wavelengths as can be observed in Fig. 6 for n_w equal to 50 and 100. What happens is that as the load increases, the probability of contention increases and therefore the deflection probability at care nodes d increases, thus increasing the hop count H.

In Fig. 5, we also compare the effectiveness of wavelength conversion to that of optical delay-line buffering. The bold line curve indicates the delay/throughput performance of a single-wavelength network where a single delay-line optical routing buffer is provided at the nodes [10]. Such a single buffer scheme and its control has been proven to be optimal [14]. Four or more wavelengths are needed for wavelength

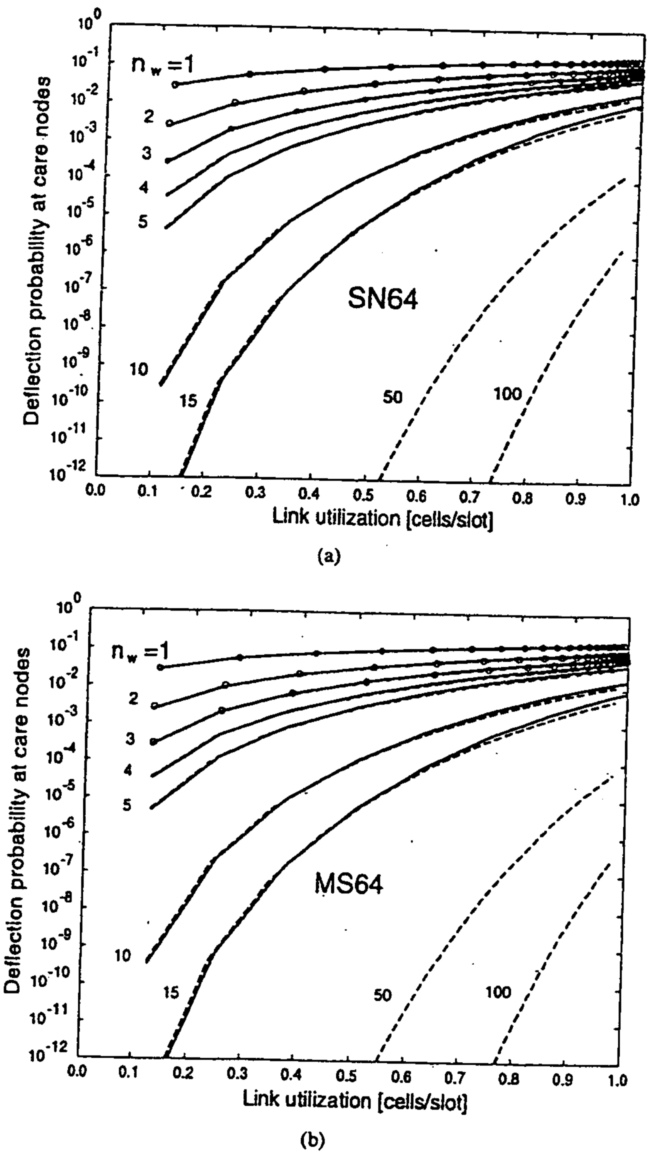

Fig. 6. Deflection probability at care nodes d versus link utilization u [cells/slot] in (a) a 64-node ShuffleNet and (b) a Manhattan Street. Number of wavelengths as a parameter: $n_w = 1, 2, \cdots, 15$. Solid lines—pooled injections (PI); circles ($n_w = 1, 2, 3$)—pooled per wavelength injections (PPWI); dashed lines—independent per-wavelength injections (IPWI).

conversion to match the contention resolution capability of a single delay-line.

This is because the number of care cells stored in the buffer (the ones causing contentions) can be made much smaller than the number of care cells circulating in the network (the ones causing contentions in wavelength conversion without buffers). Moreover, the nodes with wavelength conversion require a lot of hardware, including an $n_w \times n_w$ wavelength selection switch. In contrast, limited optical buffering in each submodule solves contentions efficiently and requires little optical hardware [15]. Therefore, from this perspective it is preferable to add buffers rather than use wavelength conversion.

However, as observed in Fig. 6, the probability of deflection is 10^{-2} at full load for a single delay-line scheme and to reduce the probability of deflection to 10^{-12} many more

optical buffers are required [16]. Such optical buffers increase the accumulation of intraband crosstalk and ASE noise, which may severely degrade the quality of received signals [17].

Further research is needed to assess whether a delay-line-only, a wavelength-conversion-only, or a hybrid delay-line/wavelength-conversion scheme offers the lowest implementation cost, for a given maximum tolerated deflection probability and bit error rate on the received cells.

VIII. Conclusions

We have shown that slotted hot-potato meshed networks with 64 nodes with more than four wavelengths and full wavelength conversion can work at full load with a hop delay of less than one hop from the zero-load hop delay. The probability of deflection can be made quite low by increasing the number of wavelengths but as the load increases, the number of wavelengths required may become exceedingly large.

An interesting finding of this study is that the simplest noncoordinated per-wavelength access scheme works more efficiently than the other more complex and greedy schemes, and should therefore be preferred. The reason is that the greedy schemes, while seeking to maximize the number of new cell injections per slot, may decrease the ability of the wavelength conversion block to solve contentions.

Results also indicate that using delay-line optical buffers at the node is a much more effective way of solving contentions than using wavelength conversion: four or more wavelengths are needed in nodes without buffers and with wavelength conversion to match the performance of nodes with one delay-line optical buffer per wavelength and without wavelength conversion.

However, delay-line optical buffers increase the accumulation of intraband crosstalk and ASE noise, while wavelength conversion can provide noise suppression and signal reshaping [6], [7]. Hence, in WRON's with a small number of wavelengths it may be preferable use optical buffers without wavelength conversion, when the transmission is feasible. On the other extreme, buffers are not needed with a large number of wavelengths and with full wavelength conversion. Hybrid solutions using both buffers and wavelength conversion [4] may be the best solution in intermediate cases, but further work is required to quantify the tradeoff.

Future work should also address a combined teletraffic/transmission performance analysis of routing with delay-lines/wavelength-conversion, both in transparent and semitransparent WRON's. An analysis is required that considers the regeneration on converted cells [6], [7] and the transmission impairments such as intraband crosstalk and ASE noise [17], [18] accumulated by cells with long, all-optical paths.

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